COMPARISON OF INITIAL AND LONG-TERM TRANSFER LENGTHS DETERMINED FROM INTERNAL AND EXTERNAL CONCRETE STRAIN MEASUREMENTS

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ABSTRACT

Transfer length in pretensioned concrete members can be determined by measuring concrete surface strains near the ends of the members and determining the point at which surface strains reach a plateau. Transfer length can also be estimated from the amount of prestressing tendon end-slip. Although both methods provide reasonable approximations at the time of detensioning, over time, the measured additional end-slip of prestressing tendons often indicates a longer transfer length than would be calculated from long-term concrete surface-strain measurements.

A pilot study was conducted at a precast/prestressed concrete institute member plant in order to evaluate transfer lengths in pretensioned concrete railroad ties using internal concrete strain measurements and measurements at the concrete surface. Internal concrete strains were determined from a series of 2-inch-long vibrating-wire strain gauges that were placed end-to-end at the centroid of prestress force at various spacings. External concrete strains were determined by embedding brass points in the concrete surface and measuring the distance between points using a Whittemore gauge.

Strain measurements and corresponding transfer-length results from each method were compared for the initial condition (immediately after de-tensioning) and after the members were eight (8) months old.

Keywords: *Prestress, Surface strains, Internal strains, Transfer length*

INTRODUCTION

The addition of longitudinal prestressing to concrete members is utilized in a wide variety of applications in order to provide increased load-carrying capacity. For example, pre-tensioned concrete railroad ties utilize the benefits of prestressing in order to provide extended service life under higher axle loads than wooden railroad ties[7]. Pre-tensioned concrete ties, consequently, have become a viable alternative to wooden railroad ties.

However, the long-term performance of prestressed concrete ties must be ensured in order to safeguard against structural failures. Reliable performance of the ties throughout their service life requires an understanding of both the magnitude and location where the prestressing force is transferred to the concrete member. The distance from the end of the member to the point where the prestress force is fully effective is commonly referred to as either the "transfer length[2]" in the United States or the "transmission length" in other countries.

In a pre-tensioned concrete member, transfer length can be influenced by many factors[6, 9, 15, 16, 17] such as concrete release strength, surface condition and geometry of the prestressing steel, concrete mix proportions, presence of viscosity-modifying or retarding admixtures in the concrete mixture, consistency of concrete mix, water-to-cementitous ratio of concrete mix, and age of the concrete member.

Transfer of prestressing force to the concrete member causes strains in the concrete member that vary with the magnitude of prestressing force transferred at a given location. For members having a constant cross-section, the longitudinal compressive strain in the concrete reaches a plateau after the prestress force has been fully transferred to the concrete. Hence, the transfer length of a pre-tensioned concrete can be determined from measurements of concrete strain on the surface of the member [6, 9], by determining the location where the surface strain transitions to a near-constant value.

Although measurement of concrete surface strain can be readily accomplished by using a mechanical (Whittemore type) strain gage, there have been concerns that these surface strain measurements may not accurately reflect the strain condition at the centroid of the cross section due to shear lag, and especially after considerable creep and shrinkage of the concrete has occurred. This research program compares the transfer lengths that are determined from both concrete surface strain measurements and from internal concrete strain measurements obtained from the same pretensioned members.

For the present study, two pre-tensioned concrete railroad ties were fabricated at a precast/prestressed concrete institute (PCI) member concrete tie manufacturing plant in August 2014. These concrete ties were cast on two casting dates with similar casting conditions. Arrangements were made in order to measure internal and external strains on both concrete ties. Arrangement details are explained in the following sections.

The work described herein was conducted at a PCI member plant that sought to evaluate transfer lengths in pre-tensioned concrete railroad ties using both internal concrete strain measurements and measurements at the concrete surface. Internal concrete strains were determined from a series of 2-inch-long embedded Vibrating Wire Strain Gages (VWSGs) that were placed end-to-end along at the centroid of prestress force in the member. External concrete strains were determined by embedding brass points in the concrete surface and measuring the distance between points using a Whittemore gage.

Fabrication of concrete ties at PCI member plant

In August 2014, a research team from Kansas State University (KSU) travelled to a PCI member plant that manufactured concrete railroad ties with a constant cross-section. During this visit, four instrumented concrete ties were cast on two casting dates, two per day. Concrete mix proportions and prestress reinforcement were essentially identical for both concrete ties.

In order to measure external (surface) strains induced due to the prestressing force, brass inserts were cast on the bottom side of a concrete tie (as-cast top surface) at one-inch spacing. Forty-two brass inserts, shown in Figure **1**, were cast on concrete as-cast top surfaces on each end (live end [LE] and dead end [DE]) of the concrete tie, as illustrated in Figure **2**. A Whittemore gage having an 8-inch gage length was used to determine the concrete surface strain along the length of the tie. Since an 8-inch Whittemore gauge was used in the present study, last point that the distance could be measured with the gauge was at 34^{th} point. Therefore, a total of 34 strain measurements were taken on concrete as-cast top surfaces on each end concrete ties.

Figure 1: Brass insert used in the present study

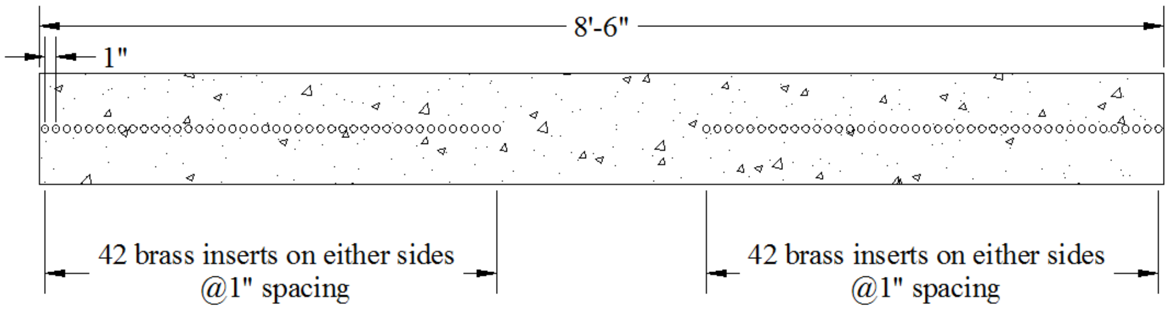


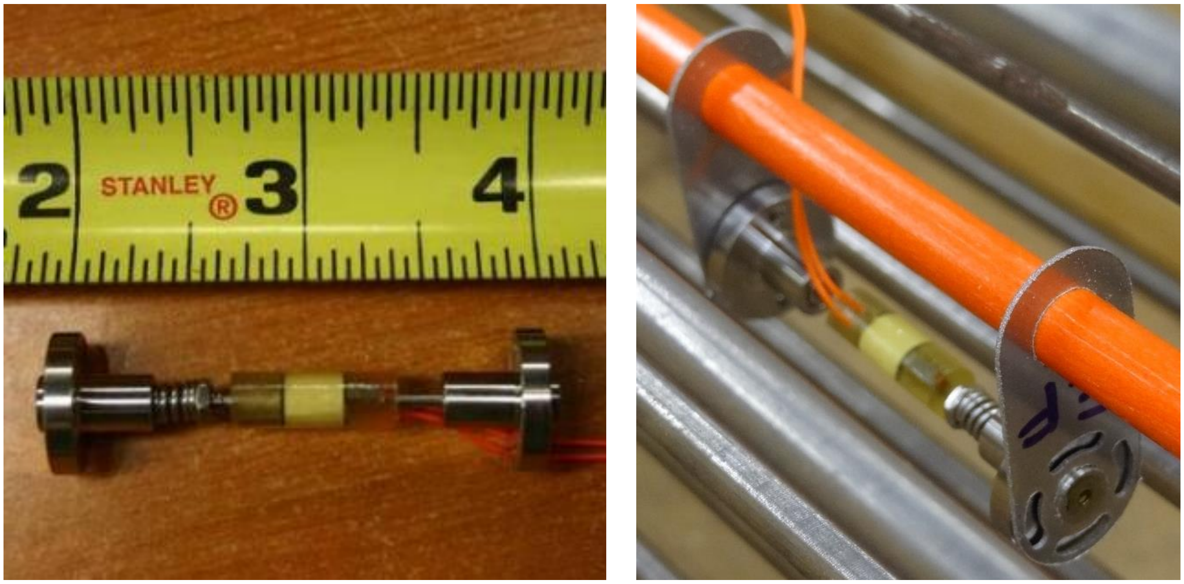
Figure 2: Brass insert layout on concrete tie bottom surface (as-cast top surface)

Internal concrete strains were determined from a series of VWSGs with a 2-inch gage length that were placed end-to-end along the centroid of prestress force at a 2 3/4-inch spacing.

Figure 3 shows photos of the VWSGs used in this study. In order to enable the precise placement of the 2-inch-long gages at 2 3/4-inch spacing, the strain gages were first secured to a fiberglass rod using special metal brackets (Figure 3b) that were precisely fabricated with a water jet. Fiberglass was chosen for the longitudinal rod since the Modulus of Elasticity of fiberglass is similar to that of concrete. At one end of the gage the metal bracket was secured to the fiberglass rod using an adhesive, while at the other end the bracket was allowed to freely slide along the fiberglass rod. This ensured that the longitudinal strain would not be restrained.

Locations of VWSGs along the length of the concrete ties are listed in Table 1. In order to distinguish VWSGs after concrete was cast, unique color tape labels were attached to each VWSG.

Each concrete tie was cast with 21 VWSGs, totaling 42 VWSGs for two concrete ties. Of these, only one VWSG was not functional after concrete placement and curing. Figure 4 shows a schematic of the concrete tie cross-section. The VWSG arrangement prior to concrete cast is shown in Figure 4 and Figure 5. Note, the concrete ties were cast in the upside-down position, such that the brass points were installed on the actual bottom surface of the tie (as-cast top face).



(a) Gage as received (b) Secured to Fiberglass Rod

Figure 3: Photos showing 2-inch VWSG[18]

Table 1: VWSGs locations along the length of a concrete tie. Note, there were VWSGs at both ends that were located symmetrically about the center line of the tie.

Gauge Location From Tie End	Gauge Color Label
2.00”	Red
4.75”	Purple
7.50”	Green
10.25”	Yellow
13.00”	Blue
15.75”	White
18.50”	Orange
21.25”	Black
24.00”	Brown
37.50”	White/Red
51” (center)	White/Blue

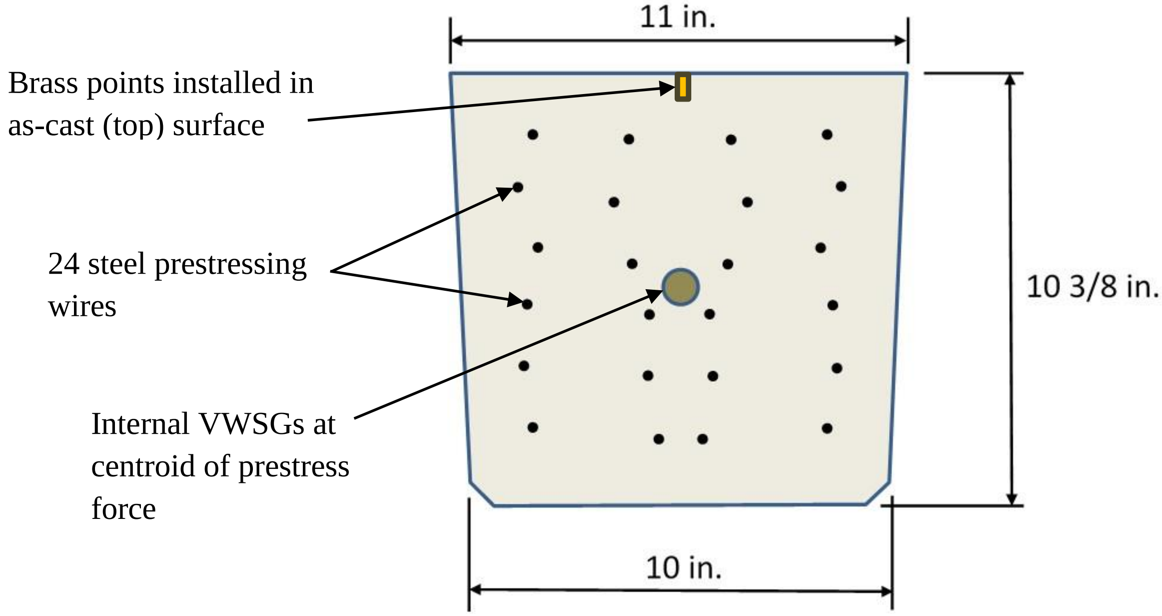


Figure 4: Concrete tie cross-section in the (upside-down) casting orientation.

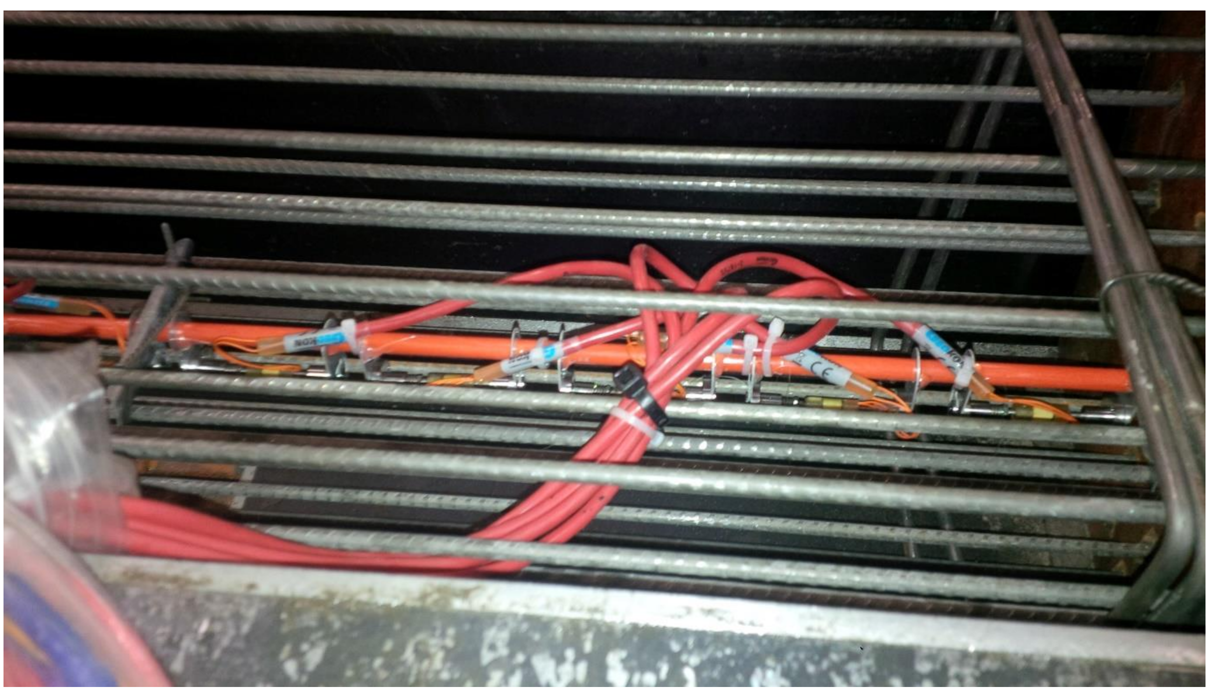


Figure 5: VWSGs secured in concrete tie form prior to casting concrete

Transfer length measurements

Transfer length by surface strains

Prior to concrete casting, 42 brass inserts with small (0.112 inches) center holes were secured to a special steel bar at precise one-inch center-to-center spacing with small screws. Two steels bars, one per end, were used for each concrete tie during the fabrication process. Figure 6 shows a concrete tie cast with the special steel bars located at each end. Prior to prestress transfer to the concrete member, the steel bars were detached from the concrete surface by removing the screws that held the brass inserts to the steel bar, and then lifting the bar upward using the transverse tubes that also kept the bars from sinking into the fresh concrete (Figure 6).

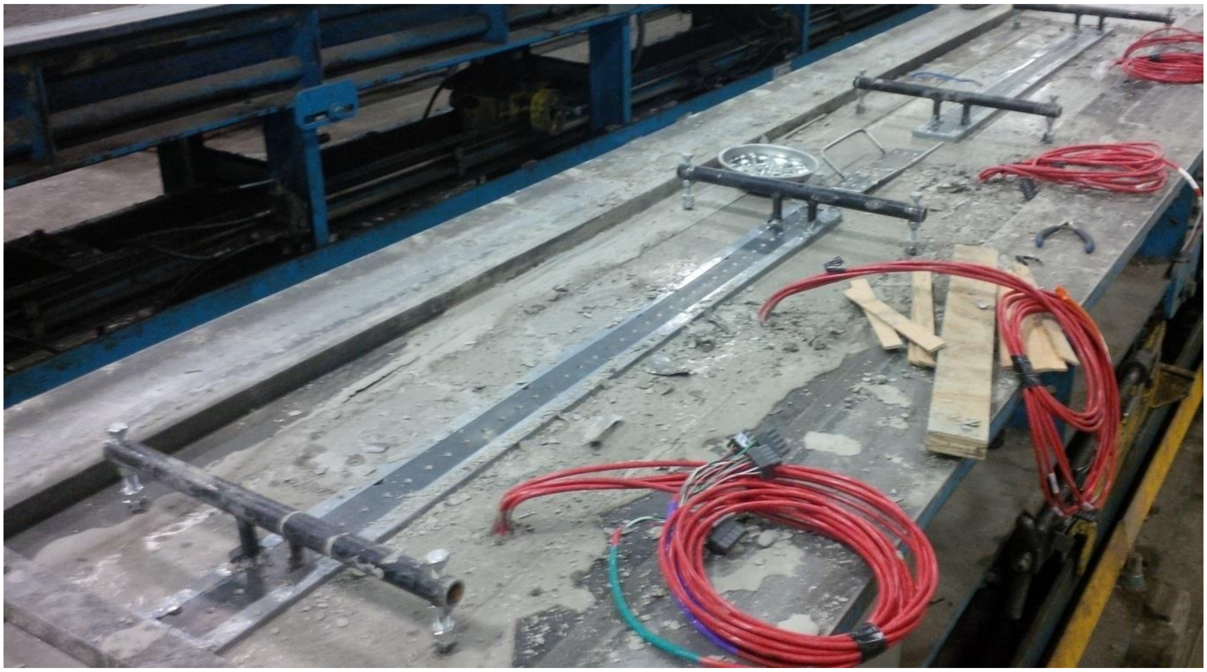


Figure 6: Special steel bars held the brass inserts at one-inch spacing on the concrete surface

The initial distances between brass inserts were then measured and recorded prior to prestress transfer. A mechanical (Whittemore) strain gauge with a precision of 0.0001 inches and an 8-inch gage length[17] was used in this work, as shown in Figure 7. Distances between these brass inserts were measured again and recorded after prestress transfer and approximately 8 months after prestress transfer. The process of distance measurement between brass inserts, shown in Figure **8**, was similar at each stage (i.e., prior to prestress transfer, after prestress transfer, and 8 months after prestress transfer).

Surface displacements were then determined by direct comparison of the Whittemore readings from before prestress transfer and the subsequent readings after de-tensioning. Surface strain values were then calculated by dividing the measured surface displacements by the gage length of 8 inches. Comparison of initial readings (before prestress transfer) and those immediately after prestress transfer were used to determine the initial transfer length. Similarly, long-term (8 months after prestress transfer) transfer lengths were evaluated by comparing surface displacements occurring between initial readings with those obtained 8 months after prestress transfer.

Figure 7: Whittemore gage with 8-inch gage length was used to obtain surface displacements

Figure 8: Distance measurement between brass inserts using Whittemore gauge

The determination of transfer lengths from the surface strain data was accomplished using the 95% AMS Method [10]. Although surface strain profiles are not included in the current section of this paper, detailed surface strain profiles are presented in subsequent sections.

Nomenclature

In this paper, the two instrumented concrete are referred to as Tie#1 and Tie#2, respectively. In addition, there are two ends for each concrete tie. The "live end" of each tie, the end located nearest to the reinforcement stressing jacks during fabrication, is denoted as "LE" while the other end of each tie was denoted as "DE" for "dead end". Both of the concrete ties fabricated in this study were prismatic members without any side scallops.

Transfer length by internal strains

Internal concrete strains were determined from a series of 2-inch-long VWSGs that were placed end-to-end at the centroid of prestress force at a 2 ¾-inch spacing. Locations of these VWSGs along the length of the concrete ties are listed in Table 1. Proper care was taken in order to safeguard the VWSGs from damage during the concrete casting process. Concrete was not placed directly on top of VWSGs. Instead, concrete was placed immediately adjacent to the locations containing VWSGs and then vibrated laterally into place around the VWSGs. **Error! Reference source not found.**

After the concrete was cast and prior to prestress transfer, strain readings and temperatures were recorded using internal thermistors that were installed adjacent to the VWSGs. A portable vibrating-wire gage reading device was used to record strain and temperature data. Similarly, measurements (strain and temperature measurements) were recorded after detensioning and 8 months after detensioning.

Internal temperature readings were used to correct for thermal shifts due to the cooling of concrete between the strain readings before and after de-tensioning. The corrected internal strain values were then used to determine the transfer lengths by the 95% AMS Method [10]. Detailed internal strain profiles are discussed in the subsequent parts of the present paper.

Results and discussion

Strain measurements and corresponding transfer length results from each method (surface strains and internal strains) are presented in this section. For both methods, transfer lengths were evaluated at initial condition (immediately after de-tensioning) and after the members were 8 months old.

Surface strains and corresponding transfer lengths

Figure 9**Error! Reference source not found.** and Figure 10 show the surface strain profiles for Tie#1 LE and Tie#1 DE, respectively. Figure 11 and Figure 12 show surface strain profiles for Tie#2 LE and Tie #2 DE, respectively. Transfer lengths obtained through evaluation of surface strain profiles for both concrete ties are tabulated in Table 2.

With the exception of Tie#2 LE, Table 2 shows that there was an expected growth in the transfer length over time (8 months); however, this growth is not consistent. The average transfer length at de-tensioning was 12.1 inches, while the average transfer length after 8 months was 13.8 inches. This corresponds to an average increase of 15.1 percent.

Table 2: Transfer lengths (in inches) evaluated from surface strain profiles

		At de-tension	After 8 months	% Increase
Tie#1	LE	11.8	14.7	24.3%
	DE	11.7	11.9	1.3%
Tie#2	LE	13.8	13.4	-3.0%
	DE	10.9	15.0	37.8%
	Averages	**12.1**	**13.8**	**15.1%**

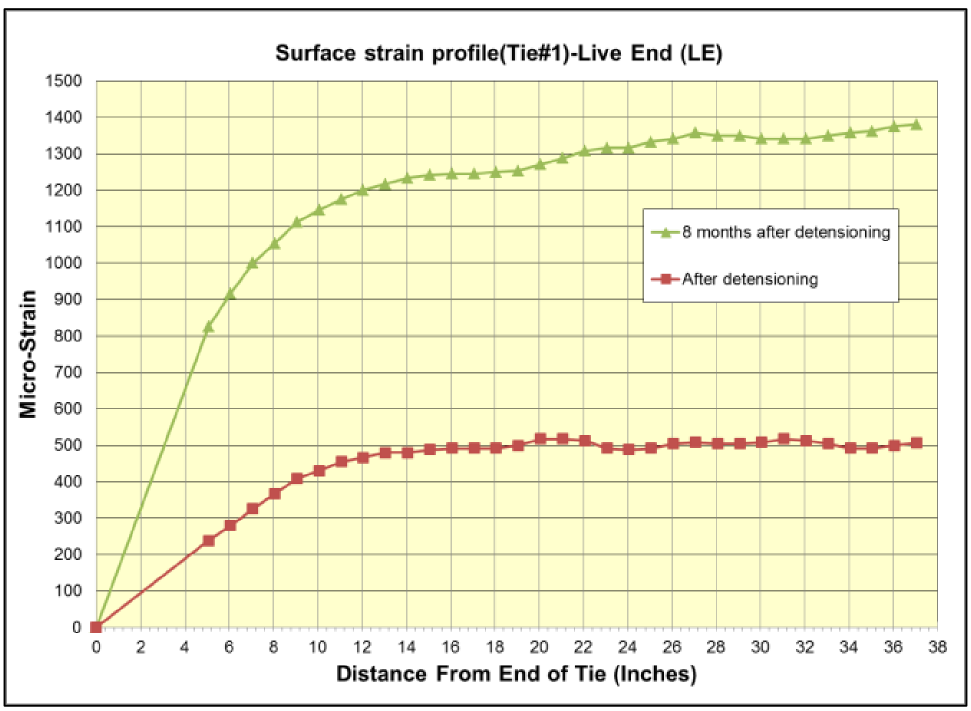


Figure 9 Surface strain profile for Tie#1 LE

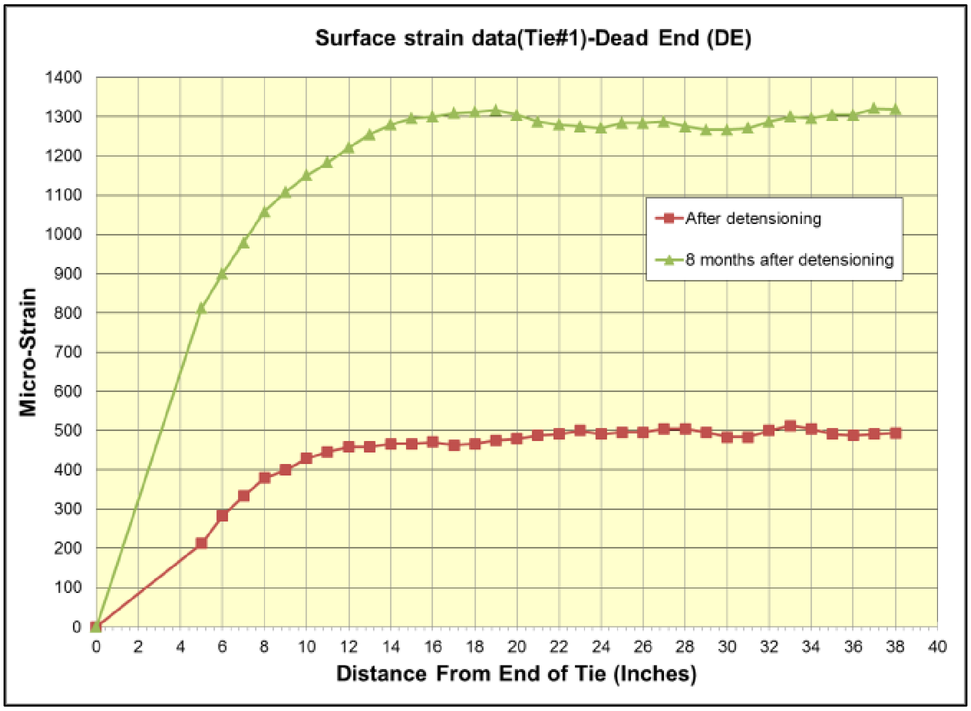


Figure 10 Surface strain profile for Tie#1 DE

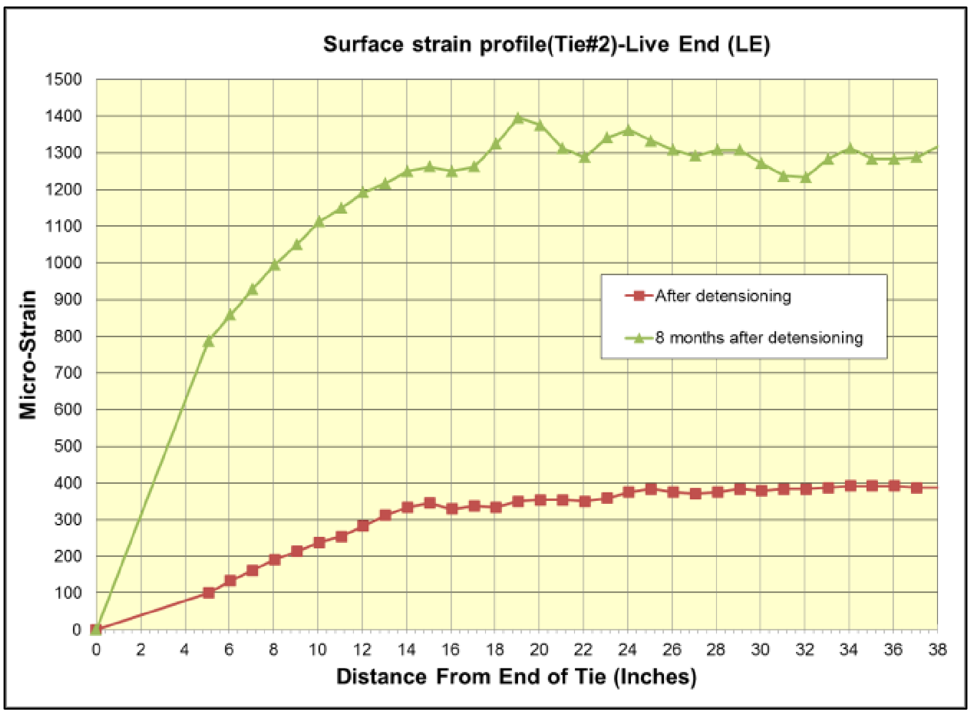


Figure 11 Surface strain profile for Tie#2 LE

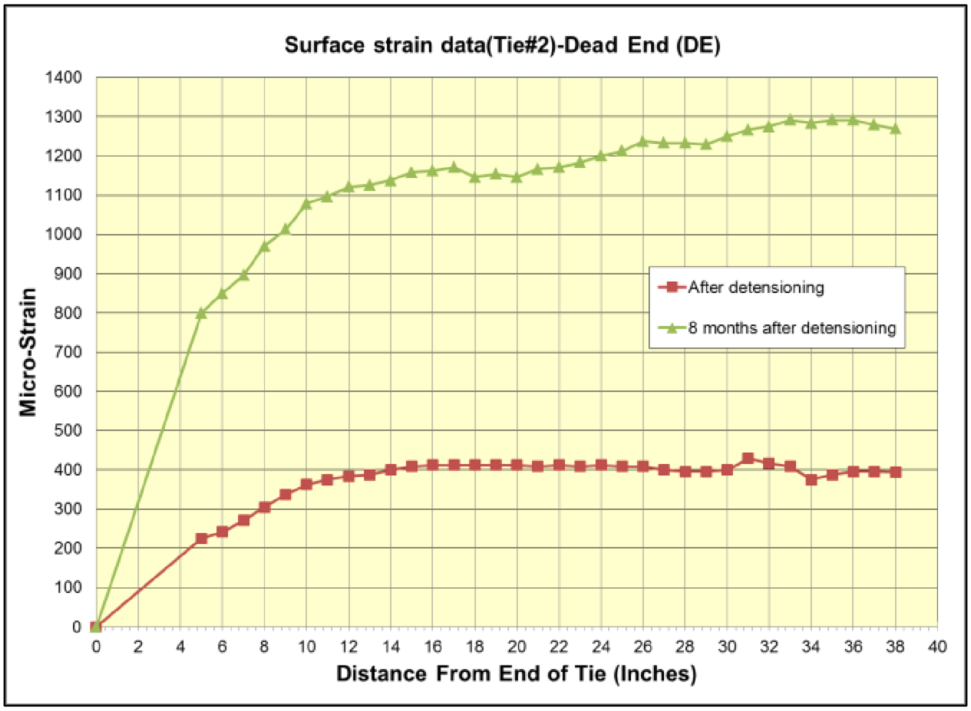


Figure 12 Surface strain profile for Tie#2 DE

Internal strains and corresponding transfer lengths

Figure 13 illustrates internal strain profiles for Tie#1 LE and Tie #1 DE, while Figure 14 shows LE and DE internal strain profiles of Tie#2. Transfer lengths were evaluated using these internal strain profiles for both concrete ties, as recorded in Table **3**. With the exception of Tie#2 LE, Table 3 shows that there was an expected growth in the transfer length over time (8 months); however, this growth is not consistent. The average transfer length at de-tensioning was 8.7 inches, while the average transfer length after 8 months was 9.3 inches. This corresponds to an average increase of 8.5 percent.

Table 3: Transfer lengths (in inches) evaluated from internal strain profiles

		At de-tension	After 8 months	% Increase
Tie#1	LE	8.0	9.0	13.0%
	DE	7.2	8.4	17.5%
Tie#2	LE	10.8	10.3	-4.2%
	DE	8.7	9.4	7.8%
	Averages	**8.7**	**9.3**	**8.5%**

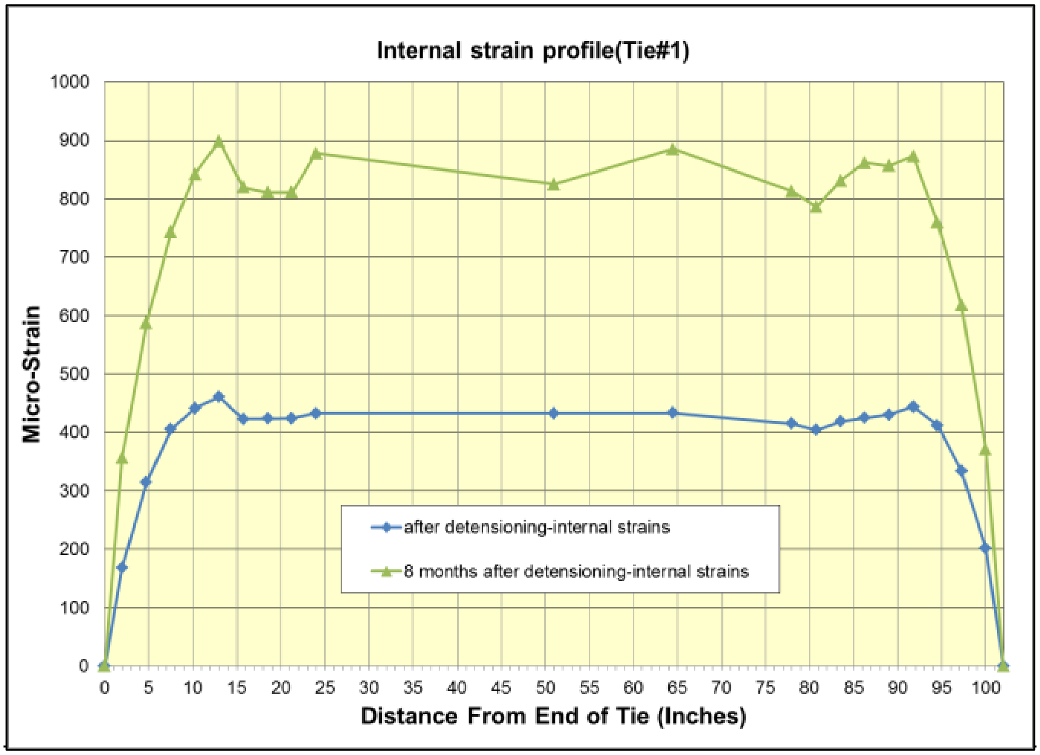


Figure 13 Internal strain profiles for Tie#1 (LE and DE)

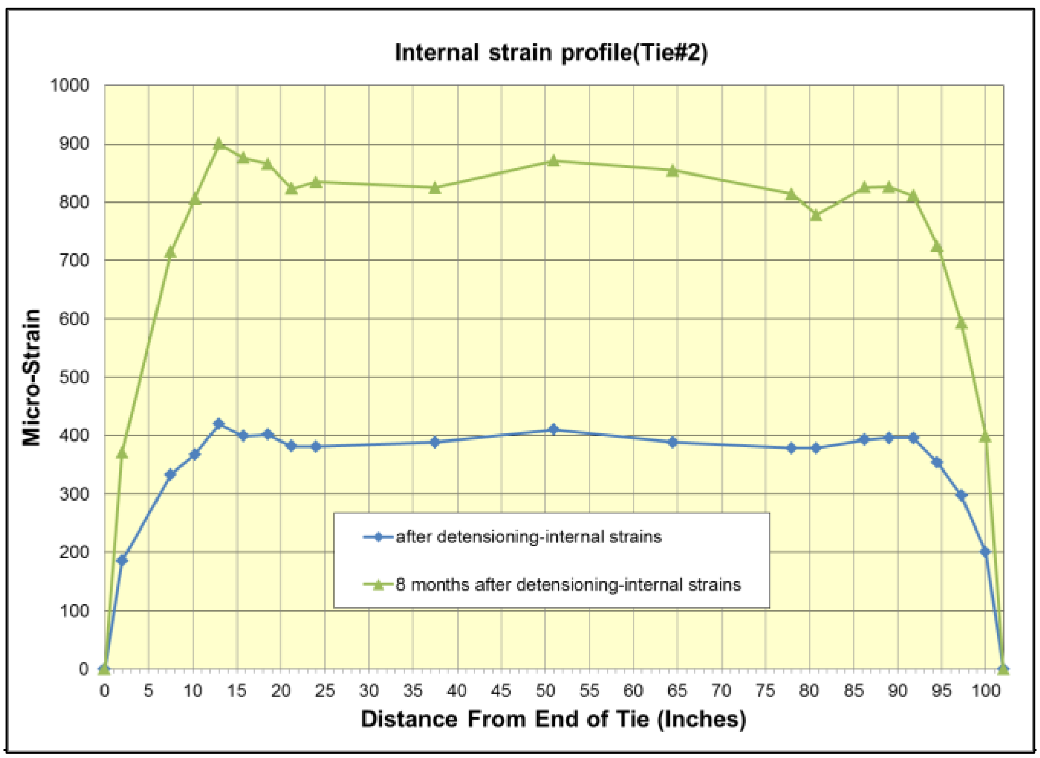


Figure 14 Internal strain profiles for Tie#2 (LE and DE)

Internal strains versus surface strains (transfer lengths)

This section presents the measured internal strain and surface strain data, along with the corresponding values of transfer length. Table 4 lists the transfer length values obtained from both strain measurements immediately after de-tensioning, while Table 5 lists the corresponding transfer lengths that were determined after the concrete ties were 8 months old. From Table 4 and Table 5, the transfer lengths determined from internal strain measurements were significantly shorter than those determined from external (surface) strain measurements at the same locations. The transfer lengths determined from concrete surface strains were, on average, 1.41 times the corresponding values determined from internal strain measurements after de-tensioning. This same ratio was 1.48 after 8 months.

The fact that the transfer lengths determined from external strain measurements are consistently longer than those determined from internal strain measurements suggests that there may be a significant shear lag occurring across the width of the tie.

Figure 15 plots a comparison of surface and internal strain data for Tie#1 immediately after de-tensioning, while Figure 16 shows the strain data recorded after 8 months. Figure 17 and Figure 18 depict the same comparative data for Tie #2, respectively.

Table 4 - Transfer Lengths determined after de-tensioning

		Surface	Internal	Difference	Surface/ Internal
Tie#1	LE	11.8	8.0	3.8	1.48
	DE	11.7	7.2	4.5	1.63
Tie#2	LE	13.8	10.8	3.1	1.29
	DE	10.9	8.7	2.2	1.25
	Averages	**12.1**	**8.7**	**3.4**	**1.41**

Table 5 - Transfer lengths determined after 8 months

		Surface	Internal	Difference	Surface/ Internal
Tie#1	LE	14.7	9.0	5.7	1.63
	DE	11.9	8.4	3.4	1.41
Tie#2	LE	13.4	10.3	3.1	1.30
	DE	15.0	9.4	5.6	1.60
	Averages	**13.8**	**9.3**	**4.5**	**1.48**

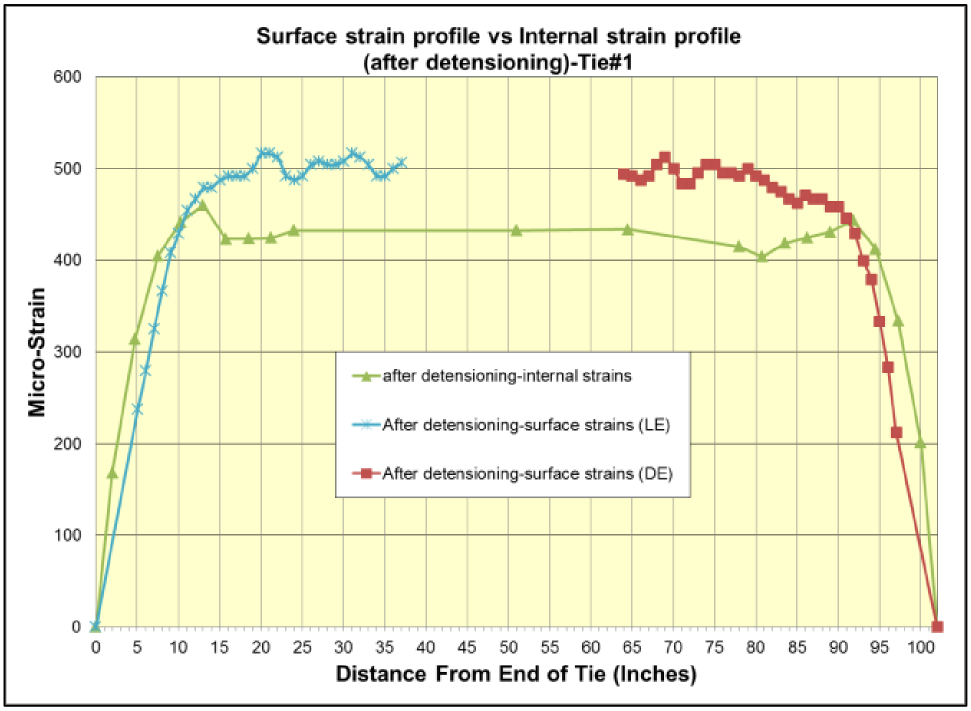


Figure 15 Tie #1 - Immediately after transfer of prestress force

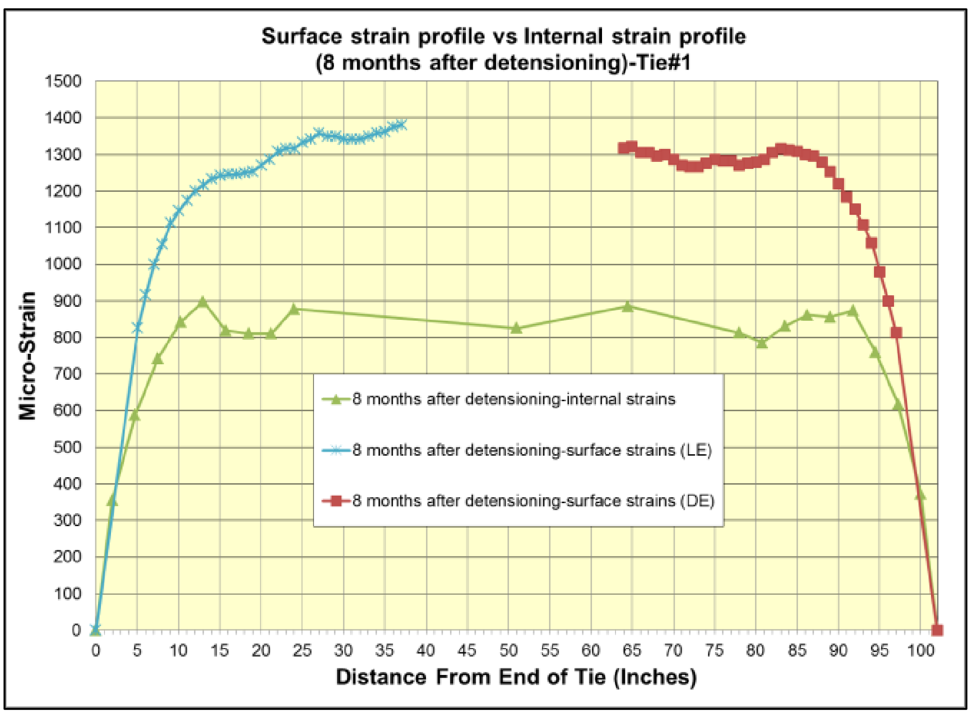


Figure 16 Tie #1 - 8 months after transfer of prestress force

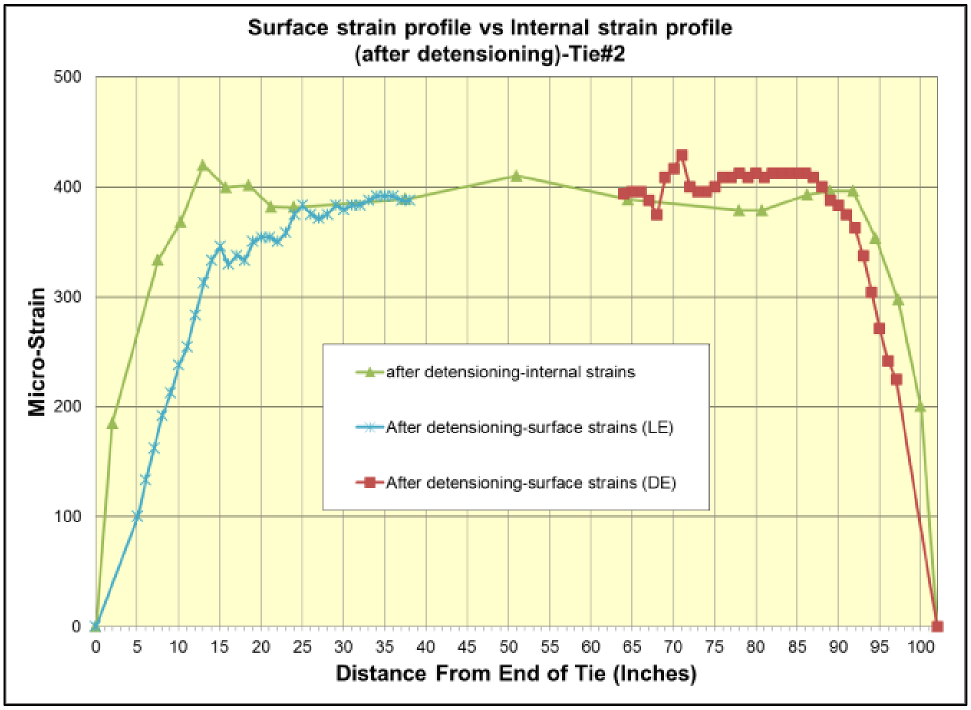


Figure 17 Tie #2 - Immediately after transfer of prestress force

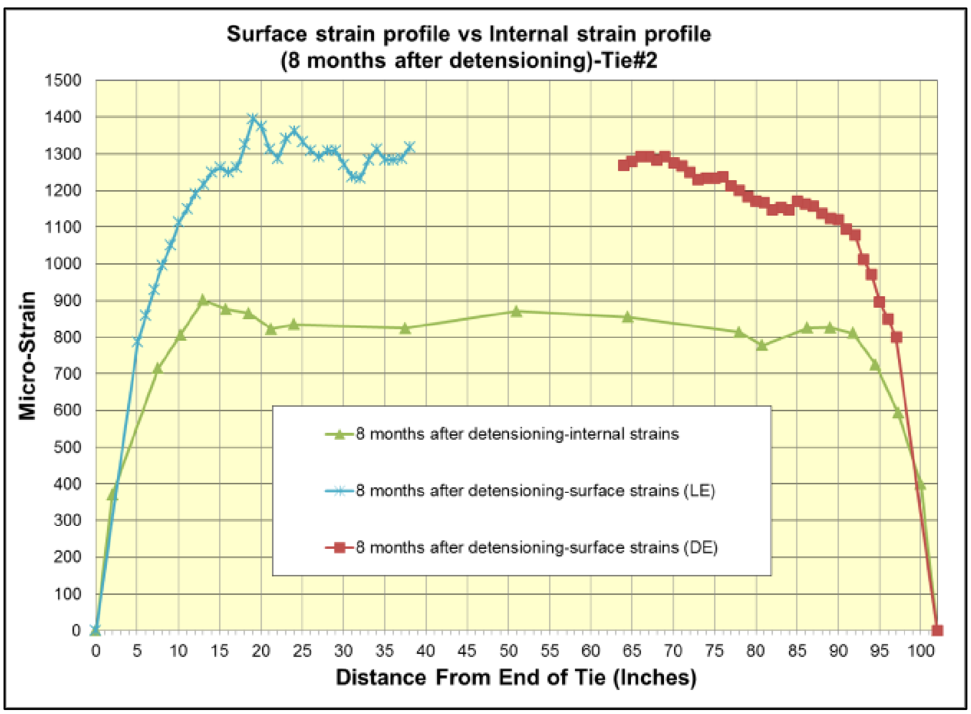


Figure 18 Tie #2 - 8 months after transfer of prestress force

Immediately after de-tensioning, the internal and external (surface) peak strain values differed only by small magnitudes (Figure 15 and Figure 17), likely due to the fact that concrete strains are mostly elastic at this point as significant creep strain has not yet occurred. Figure 15 shows that Tie #1 had the largest differential in peak strain values, with approximately 430 με internal versus approximately 500 με external. This difference might be attributed to the difference in reading time, as different persons were assigned to take Whittemore readings and VWSG readings. Thus, there may have been as much as 45 minutes difference in the time between the two sets of readings with additional creep strain occurring prior to the Whittemore readings being taken. Note, for Tie #2 the internal and surface strain plateaus were nearly identical at approximately 400 με (Figure 17).

However, after 8 months, significantly higher magnitudes of strain were recorded at the concrete surface compared to the internal strain measurements. Fir Tie #1, the surface strain plateau was approximately 1300 με compared to an internal strain plateau of approximately 900 με. For Tie #2, the corresponding strain plateaus were similar. The general increase in concrete strain levels can be attributed to creep and shrinkage of the concrete, while the higher strain values at the surface are likely due to the increased level of drying shrinkage that had occurred at that location.

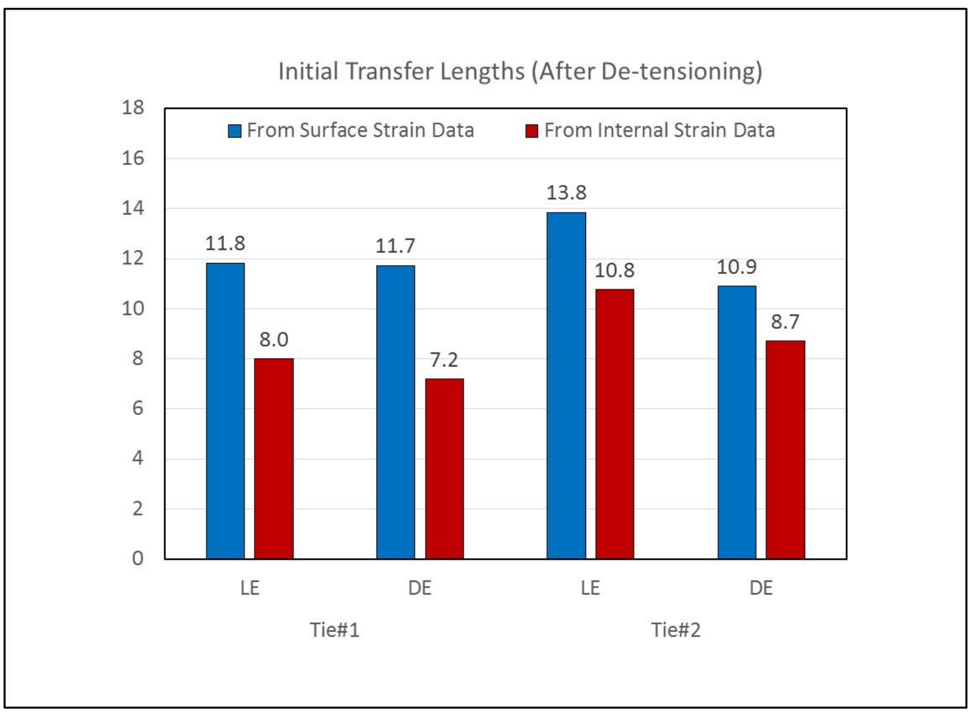


Figure 19: Chart showing transfer lengths at de-tensioning

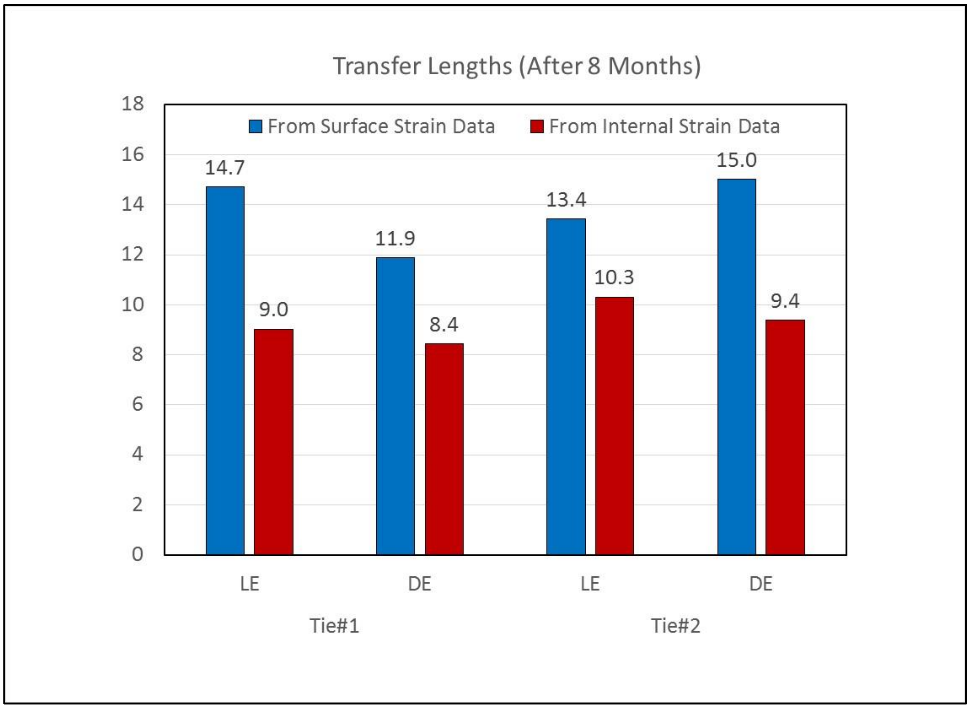


Figure 20: Chart showing transfer lengths after 8 months

Conclusions

The following conclusions are drawn from the work presented in this paper:

1. The maximum concrete strain levels at the surface and at the centroid of prestress force are approximately equal at de-tensioning.
2. The strain in the concrete was observed to increase more rapidly at the centroid of the concrete than at the surface, resulting in longer transfer lengths being determined for the surface strain measurements. These differences were 3.4 inches, on average, at de-tensioning and 4.5 inches, on average, after 8 months. The reason for this difference is unknown, but may be partially attributed to a shear lag effect between the concrete core and surface.
3. The long-term magnitude of surface compressive strain is much larger at the surface than at the centroid of the prestressing steel. This is likely due to increased drying shrinkage occurring at the concrete surface. Therefore, long-term surface strain measurements should not be used to estimate the level of prestress loss.

Acknowledgements

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References

1. *AASHTO LRFDBridge Design Specifications*, 6th Edition.
2. ACI Committee 318. *Building Code Requirements for Structural Concrete*, 318-11, American Concrete Institute, 2011.
3. ASTM Standard C39, 2012a, "Standard Test Method for Compressive Strength of Cylinder Concrete Specimens." ASTM International, West Conshohocken, PA, 2012, DOI: 10.1520/C0039_C0039M-12A, www.astm.org.
4. ASTM Standard C469, 2010, "Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of concrete in Compression." ASTM International, West Conshohocken, PA, 2010, DOI: 10.1520/C0469_C0469M-10, www.astm.org.
5. ASTM Standard C496, 2011, "Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens." ASTM International, West Conshohocken, PA, 2011, DOI: 10.1520/C0496_C0496M-11, www.astm.org.
6. Bodapati, N. et. al., (2013). "Influence of Indented Wire Geometry and Concrete Parameters on the Transfer Length in Prestressed Concrete Crossties", Proc. 2013 Joint Rail Conference. Paper Reference #JRC2013-2463. Knoxville, TN.
7. Hanna, Amir N. "Prestressed Concrete Ties for North American Railroads." PCI Journal Sept.-Oct. 1979:32-61.
8. Kaar, Paul H., N. W. Hanson. "Bond Fatigue Tests of Beams simulating Pretensioned Concrete Crossties." PCI Journal 20.5 Sept. - Oct. 1975: 65-80.
9. Murphy, R., (2012) Determining The Transfer Length In Prestressed Concrete Railroad Ties Produced In The United States. Thesis. *Kansas State University, Kansas.*
10. Russell, B. W., and N. H. Burns. 1993. Design Guidelines for Transfer, Development and Debonding of Large-Diameter Seven-Wire Strands in Pretensioned Concrete Girders,1210-5F, Center for Transportation Research, the University of Texas at Austin, Austin, Tex., Jan. 1993, 300 pp.
11. Srinivasa Rao, P., P. Kalyanasundaram, and M. F. Sharief. "Transmission Length of Ribbed Bars in Pre-Tensioned Concrete." The Indian Concrete Journal 51.5 May 1977: 149-153.
12. Zhao, W. (2011). *Development of a Portable Optical-Strain Sensor with Applications to Diagnostic Testing of Prestressed Concrete.* Dissertation. *Kansas State University, Kansas.*
13. Zhao, W., K. Larson, R. Peterman, T. Beck, and J. Wu. "Development of a Laser-Speckle Imaging Device to Determine the Transfer Length in Pre-Tensioned Concrete Members." *PCI Journal* 57.1 Winter 2012: 135-143.

14. Zhao, W. et. al., (2013). "A Direct Comparison of the Traditional Method and a New Approach in Determining 220 Transfer Lengths in Prestressed Concrete Railroad Ties", Proc. 2013 Joint Rail Conference. Paper Reference #JRC2013-2469. Knoxville, TN.
15. Barnes, Robert W., J.W. Grove, and N.H. Burns. "Experimental Assessment of Factors Affecting Transfer Length." *ACI Structural Journal* 100.6 Nov. – Dec. 2003: 740-748.
16. Bodapati, N. et. al., (2014). "effect of concrete parameters on transfer length of concrete ties", Proc. 2014 Joint Rail Conference., Colorado Springs, CO.
17. Bodapati, N.N.B. et. al., (2013). "Transfer-Length Measurements on Concrete Railroad Ties Fabricated With 15 Different Prestressing Reinforcements," Proc. 2013 PCI Convention and National Bridge Conference. Paper Reference #148. Grapevine, TX.
18. Holste, J., (2014) Experimental Determination of Prestressing Wire Bond and Splitting Propensity Characteristics through Tensioned Pullout Tests. Ph.D. Dissertation. *Kansas* State University, May 2014.